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ORIGINAL ARTICLE

Phosphorus availability on many organically managed farms in Europe

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Abstract Maintaining sufficient soil phosphorus (P) levels for non-limiting crop growth is challenging in organic systems since off-farm inputs of P are restricted. This study assessed the status of P on organic farms in Europe using soil test results for extractable P. Data was obtained from published literature, unpublished theses, and various national and regional databases of soil test values. Most of the data (15,506 observations) came from field scale soil tests, but in some cases (1272 observations) values had been averaged across a farm. Farm scale and field scale data were analysed separately and the impact of farm type (arable, dairy, grassland, horticulture, mixed, poultry, unknown) was assessed. Soil test results were assigned to P classes from very low (P class 1) to very high (P class 5). The farm scale data came primarily from Norway, Sweden and Switzerland and did not indicate deficiencies in extractable P; 93% of farms fell into class 3 or above. The majority of the field scale data came from Germany and indicated

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sufficient or higher levels of P availability for arable and grassland systems on 60% of fields; the remaining fields had low or very low available P. Adaptations in organic systems may improve P uptake and utilization efficiency allowing yields to be maintained in the short-term, nevertheless there is cause for concern about the long-term P sustainability of some organic farming systems in Europe. This highlights the need to reassess allowable P inputs in organic farming systems to improve overall sustainability.

Keywords Soil test P · Organic agriculture · Ecological agriculture · Agroecology · Phosphorous · Agricultural sustainability

Introduction

The phosphorus problem in organic agriculture

Phosphorus (P) is an essential nutrient in agriculture and a key element in many physiological and biochemical processes. In the natural environment, P removals from the soil solution are compensated for through the desorption of soil P adsorbed on soil colloids, mobilization of Ca-, Fe- and Al-phosphates, weathering and dissolution of rocks and minerals with very low solubility, or through the mineralization of P from organic pools (Brady and Weill 2002). In agricultural systems, the slow rates of P release from these sources has led to the use of supplementary P inputs (e.g. inorganic fertilizers, animal manures, recycled P fertilizers) to optimise crop productivity and offset P removals in harvested crops. Conventional farmers ensure adequate supply of P through regular additions of water-soluble phosphate fertilizers which are formed from the acidification of P-containing rocks such as apatite. Organic farmers are prohibited from using soluble mineral P fertilizers according to EU regulations (European Union 2007, 2008). This ban is partly related to the principles of organic farming that emphasize a reliance on biologically active soils to provide crop nutrients (Lampkin and Measures 2001). There are also concerns about the environmental impact of mineral P fertilizer production and the long-term sustainability of food systems that rely on a mined, non-renewable resource to maintain productivity (Soil Association 2010).

As a consequence of these concerns, European organic crop production regulations allow only three categories of P inputs: phosphate rocks, a restricted list of P-containing recycled organic materials (e.g. composted or digested source-separated household waste, meat and bone meal), and animal manures (Annex 1, European Union 2008; Løes et al. 2017). All of these sources have limitations. Phosphate rocks can be very inefficient P sources in soils with a pH > 6.0 (Fardeau et al. 1998) so that the rate of P release is insufficient for optimal plant growth. The list of P-containing recycled organic materials includes so many regulatory restrictions on production processes and composition that in practice most of these sources are not allowable in organic systems (Løes et al. 2017). Animal manure is allowed from organic units as well as conventional farms with justification, provided that it is not the output of 'factory farming' (European Union 2008), although interpretation of this term is left to the Member States or to organic control bodies. This has led to a reliance on conventional manure sources on some organic farms which is incompatible with the basic principles of organic agriculture, as in practice it means the transfer of conventional P sources to organic farming via animal manures. There have been initiatives to phase out this practice (e.g. Denmark) and the consequences of this are discussed in detail by Oelofse et al. (2013). However, due to challenges in finding viable alternatives, the decision of the two main organic agricultural organisations to phase out, and ultimately ban the use of conventional manure and straw in organic production by 2022 in Denmark has been postponed (Magid, personal communication).

An additional challenge, in both organic and conventional systems, arises from the specialisation of many farms that has occurred since the late 70s prompting a spatial decoupling of livestock and crop production systems (DEFRA 2008). This has resulted in a lack of sufficient nutrient inputs on many stockless organic farms (Martin et al. 2007), increasing the risk of soil nutrient depletion over time. Indeed, Goulding et al. (2008), Zorn and Wagner (2010) as well as Løes and Ebbesvik (2017) showed a decline in available P at the farm scale after conversion to organic management when sampled at different time points, suggesting "mining" of soil reserves built up during a prior period of conventional farming (Løes and Øgaard 2001).

Assessing the soil P status of farming systems

An estimate of the pool of plant available P in the soil can provide an indication of the soil's ability to supply P to meet crop demands. Most methods rely on an extraction procedure designed to mimic the action of roots and root exudates involved in solubilisation of P (Table 1). The extraction methods used in different countries may vary concerning parameters such as pH, extraction time, soil–solution ratio, temperature and concentration of active agents (Schick et al. 2013). In Denmark and the UK, a weakly alkaline solution of sodium bicarbonate is used (Olsen P; Olsen et al. 1954) which works by dissolving Ca-phosphates in alkaline and neutral soils and promoting desorption of P from (hydrous) iron and aluminium oxides into solution in acid soils (Olsen and Sommers 1982). Both the double lactate (P-DL) and calcium lactate (P-CAL) extractants used in Latvia/Poland and Germany respectively, are weakly acidic and work by chelating Ca^{2+}, Al^{3+} and Fe^{3+} and promoting desorption of P (Schick et al. 2013). Likewise, Bray 1 (Bray and Kurtz 1945) is a weak solution of HCl and NH_4F suitable for soils with pH < 7.5. The solution promotes P desorption through formation of aluminium–flouride complexes. Ammonium lactate (P-AL; Egnér 1954) used commonly in Lithuania, Sweden and Norway is still more acidic and has a higher concentration of chelating anions than P-DL or P-CAL, making it suitable for analysis of soils containing up to 20% $CaCO_3$ (Schick et al. 2013). Converting the results from one extraction method to another depends largely upon soil characteristics and is therefore not generally valid (Sibbesen and Sharpley 1997).

The conventional approach for determining P fertilizer needs is to convert extractable P to a soil P index or class (Table 1) and correlate the class with the expected crop response to added P fertilizer. High additions of P are recommended at very low or low soil P levels to increase extractable P pools, and maintenance applications (P supplied to replace crop removal) are recommended when soil test values fall into the middle P class. With very high P availability, P fertilization should be restricted.

The applicability of conventional soil test P extractants and related P classes in organic agriculture has been questioned. Yields in organic systems are primarily limited by N availability and are usually lower than conventional yields (Seufert et al. 2012), hence they have a lower P demand which may be met by mineralization of organic compounds, a process not directly measured by conventional P extractants (Steffens et al. 2010). It might be argued that the field experiments used to validate soil test results account for mineralization of P from organic compounds. However, inputs of organic nutrient sources as well as the reserves of organic P may be higher in organic systems and the biological activity that promotes soil organic matter mineralization may be enhanced by organic farming practices (Nesme et al. 2014). It is therefore possible that conventional soil testing methods underestimate P availability from organically managed soils (Steffens et al. 2010). In spite of the limitations associated with using conventional P extractants to indicate soil P availability in organic systems, most published research uses these standard methods even in organic farming studies (see Table 2).

Recent developments in electronic record keeping and the processing of large data files have made it possible to conduct evaluations of large databases of soil test results. Results of such an analysis could support the organic sector to assess the sustainability of P use and highlight the need for further innovations in P management. They may also inform future discussions about organic farming regulations, both within the European Union, and globally. In this study we used data sourced from European countries, primarily Germany and Norway, to address the immediate question: What is the soil P status of land under organic management? We used the results of

Table 1 P classes for extractants used in this study

P class	P-AL[a]	P-CAL[b]	P-DL[a]	Olsen[c]	Bray[d]
1	0–20	0–20	0–22	0–9	0–15
2	21–40	21–44	23–44	10–15	16–20
3	41–80	45–90	45–65	16–25	21–25
4	81–160	91–150	66–87	26–45	26–35
5	> 160	> 150	> 87	> 45	> 35

All concentrations in mg P kg^{-1}

[a]Schick et al. (2013), [b]Kerschberger et al. (1997), [c]Defra (2010), [d]Mallarino et al. (2013) and Schick et al. (2013)

Table 2 Summary of sources and characteristics of soil P data used in this study

Source	Country	Extractant	Data type	Scale	N[a]
AGES (2010); means extracted from report	Austria	P-CAL	Monte Carlo	Field	192
Gosling and Shepherd (2005); means extracted from paper	UK	Olsen	Monte Carlo	Field	16
Kolbe (2015); raw data used in conference paper[b]	Germany	P-CAL	Real	Field	9932
Bosshard (1999); raw data used in MSc thesis	Switzerland	P-DL	Real	Farm	85
Leisen (2013); raw data used in conference paper[b]	Germany	P-CAL	Real	Field	4074
Lindenthal (2000); raw data used in thesis	Austria	P-CAL	Real	Field	506
		P-DL			177
Løes and Øgaard (1997); means extracted from paper	Norway	P-AL	Real	Farm	12
Løes and Øgaard (2001); means extracted from paper	Norway	P-AL	Real	Farm	5
Grønlund 2010–2015; raw data from database	Norway	P-AL	Real	Farm	1163
Möller; raw data from unpublished survey 2013 and 2014	Germany	P-CAL	Real	Field	559
Romanya and Rovira (2007); means extracted from paper	Spain	Olsen	Monte Carlo	Field	8
Van Den Bossche et al. (2005); means extracted from paper	Belgium	P-AL	Real	Field	42
Williams and Hedlund (2013); means extracted from paper	Sweden	Bray-1	Monte Carlo	Farm	7

[a]Number of observations in the final dataset

[b]P class data was generated from the raw data provided using the number of samples included in the survey and proportions of samples in each of the five P classes

this analysis to explore the wider question: What factors, including farm type, affect the soil P status on organic farms? We also explored the limitations associated with the use of soil test results to evaluate P status on organic farms.

Materials and methods

Data collection

For the purposes of this paper, soil extractable P at a given time, classified as very low (1), low (2), medium (3), high (4) or very high (5) according to national assessment systems, is used as an indicator of soil P status (Table 1). Data indicating the soil P status of organically managed individual fields and farms (values for several fields averaged across the farm) in Europe was collated from published studies in refereed academic journals and conference proceedings, as well as non-refereed "grey literature" (theses and reports). Raw data used in a number of published and unpublished studies was also provided by individual scientists with links to the authors (e.g. Germany: Kolbe, Möller; Switzerland: Bosshard; Austria: Lindenthal; Norway: Grønlund) as indicated in Table 2. The raw data was screened to ensure that duplicate measurements from the same field were not included. For example, since soil samples in Norway are normally taken once every 5 years, we chose just one 5 year period for extraction of the data. We also removed any values that were clearly duplicates from the same fields. Results are presented at the field or farm scale (Table 2).

A survey of peer-reviewed published literature in the ISI-Web of Science between 1990 and 2016 was conducted to identify papers reporting results from studies on soil P status on organic farms. The following search terms and their variations were used in various combinations: P/phosphorus/phosphorous, organic/ecological, farming/systems/agriculture/management, and soil. Since we were interested in assessing the actual P status on commercial organic farms, results from long-term experiments were excluded and only papers consisting of real farm surveys in Europe were included.

All relevant descriptive information and explanatory data were extracted from the data sources and compiled in excel spreadsheets. Key descriptive information extracted included: country, number of years under organic management, farm type, and P extraction method. Farm type was defined according to the groups used by Watson et al. (2002) and included: arable, beef, dairy, horticulture and mixed. Additional groups for poultry farms and grassland were added to reflect the composition of the dataset. The P extractants included ammonium acetate lactate (P-AL), double lactate (P-DL), calcium acetate lactate (P-CAL), Olsen extractant and Bray 1, which were all used in at least one study. Results for each study were converted to P classes based on national assessment systems as described above (see Table 1).

Data processing

When only summary data was available i.e. means and in some cases standard deviations grouped by farm type, a typical dataset with the number of observations equal to the value of n for each study was generated using Monte Carlo simulation in MS Excel 2010 (a total of 223 observations generated). This uses the NORMINV and RAND () functions to generate a random set of data that would have resulted in the same mean and standard deviation as the original summary data.

Standard deviations (SD) were calculated from standard errors (SE) where available using the formula,

$$SD = SE \times \sqrt{n}$$

For the AGES (2010) dataset, standard errors and deviations were not provided, but medians and quartiles were available. We used the medians and quartiles to estimate the standard deviation using the method described by Wan et al. (2014) and then generated a typical range of soil test values using Monte Carlo simulations as described above.

The data provided by Kolbe (2015) and Leisen (2013) summarized results of various soil surveys where P-CAL was the extraction method and the percentage of arable and grassland fields falling into each German P index class was provided. Using the information on percentage of fields in each class and the total number of fields included in each survey, we converted the Kolbe (2015) and Leisen (2013) data back to numbers of fields within each class and added a row for each field to our dataset. This added 14,006 observations to our database and meant that the study was heavily weighted towards German farms.

Farmers in Norway are required to test their soils for available P (P-AL) every 5–7 years. The Norwegian data provided by Arne Grønlund represents soil test values for selected fields on 41,000 farms in Norway; ~ 2500 of these are organic. The data was filtered to extract data from all the organic farms, and covered the years from 2010 to 2015 to ensure maximum coverage of organic farms, but minimal duplication of farm data. Where several fields and/or subholdings were reported for a given farm, the average value for that farm was used. No information on the farm type was available for the Norwegian dataset. A full summary of the sources of data used in the study and number of observations in the final dataset is included in Table 2.

Statistical analysis

Data analysis was carried out using the R statistical software package (www.r-project.org; (R Development Core Team 2011). Histograms showing the distribution of the observations into P classes were produced using the barplot function. Distribution by farm type and country were also assessed using barplots.

Results

There were a total of 16,778 observations in the dataset, of which 15,506 represented measurements from individual fields and 1272 represented farm scale data. The results of the analysis of the farm scale data indicate very low P (P class 1) levels in ~ 2% and low levels (P class 2) in ~ 4% of the farms (Fig. 1), with a quarter of farms surveyed falling into the sufficient (P class 3) range and ~ 68% high or very high in extractable P (P classes 4 or 5).

Overall, results from the field scale dataset indicated that ~ 62% of fields were sufficient or higher in extractable P (Fig. 2). However, there remained approximately 28% of fields that were low and 9% of fields that were very low in extractable P.

When the field scale data was disaggregated by farm type where available (Fig. 2), most fields still fell into P class 3 (sufficient). Sixty-two percent of the fields on both arable and grassland farms were sufficient or higher in extractable P, as well as 89% of fields on horticultural operations. This was in contrast to dairy farms where ~ 79% of fields were low or very low in P. The number of samples from

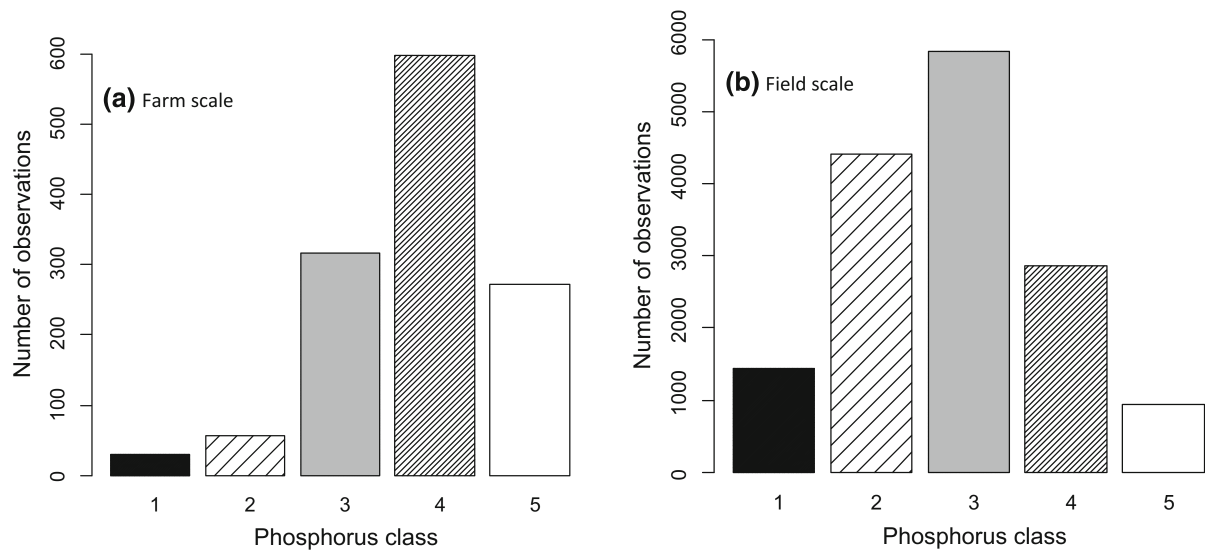
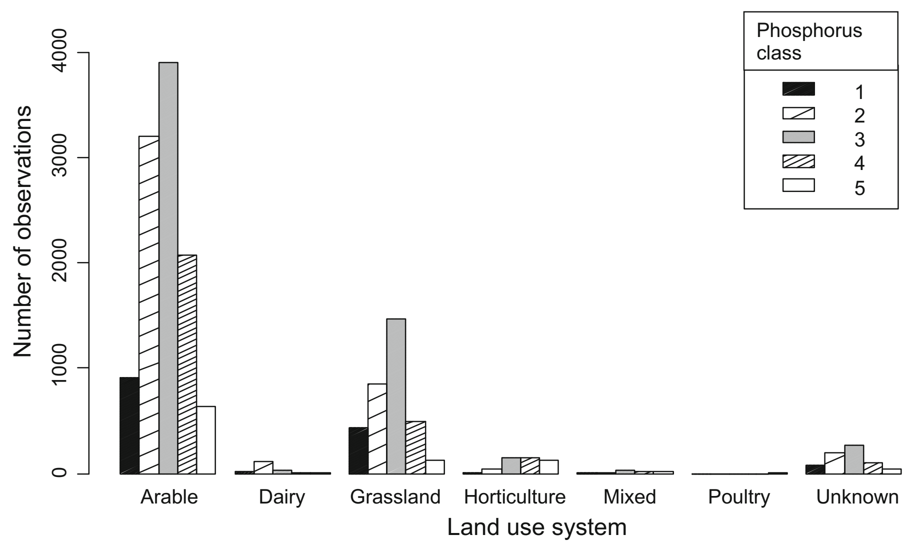


Fig. 1 Distribution of farm scale soil extractable P values among P classes ranging from very low (P Class 1) to very high (P Class 5). **a** Farm scale data. Total number of observations in the dataset was 1272. **b** Field scale data. Total number of observations in the dataset was 15,506

Fig. 2 Distribution of field scale soil extractable P values among P classes ranging from very low (P Class 1) to very high (P Class 5), disaggregated by farm type. Total number of observations in the dataset was 15,506



mixed farms in this dataset was relatively low, but they displayed a similar pattern to the farm scale data with ~ 81% of fields from mixed farms having sufficient or higher P levels. The unknown set of fields had a similar pattern of results as the arable and grassland fields, with ~ 40% low or very low in extractable P, and the remaining ~ 60% sufficient or higher.

There were some differences among countries in the distribution of soil test results among the classes (Fig. 3). In Austria ~ 12% of fields were in the very low class (P class 1) and ~ 37% were low in P (P class 2); the remaining ~ 51% had sufficient or higher P. In Germany, ~ 37% of fields were low or very low in P with the remaining ~ 63% sufficient or higher in P. Only ~ 3% of farms in Norway had low or very low soil test P values while the remaining 97% had sufficient or higher soil extractable P. In Switzerland the situation was very different with about 66% of farms having low or very low levels of extractable P

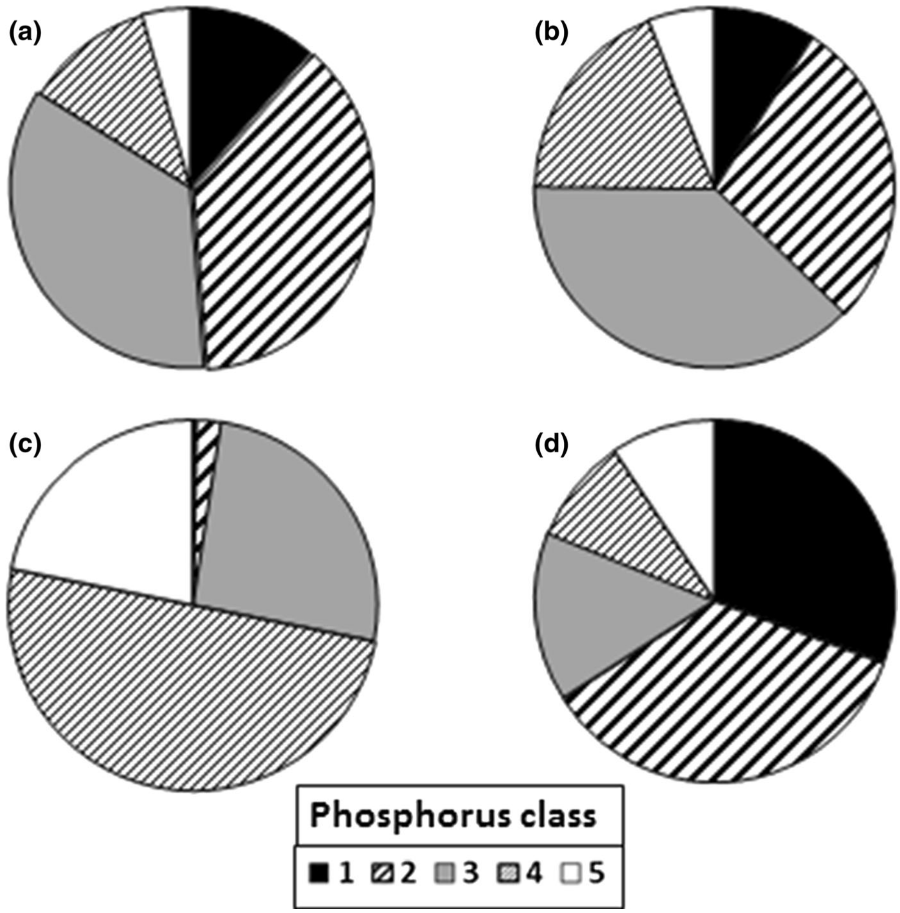


Fig. 3 Distribution of soil extractable P values among P classes at the field level in **a** Austria n = 875 and **b** Germany n = 14,565, and at the farm level in **c** Norway n = 1180 and **d** Switzerland n = 85

and only 34% with sufficient or higher soil extractable P.

Discussion

Database on soil P on organic farms

The present survey indicates that there is a weak database on the soil P status of organically managed fields across most European countries. While we did our best to obtain data from a range of European countries, in most cases this was not readily available; therefore the data are heavily skewed towards countries with links to the IMPROVE-P project. Nevertheless, the outcomes should be broadly transferable to other countries within Europe and beyond, and the country by country analysis (see Fig. 3) provides some useful information on the differences in soil P status between countries in the study which can be related to the dominant farming systems in those countries.

Another limitation was a shortage of descriptive information to accompany the soil test results, e.g. the underlying farming system, time since conversion to organic farming and level of inputs. Sources of nutrient inputs to the farms and level of exports would have been particularly useful. Originally, an objective of this work was to review data on farmgate P balances: information which would have complemented the soil test results, however, very little data on this is currently available at the farm scale. Watson et al. (2002) conducted a review of published studies on farm scale nutrient budgets on organic farms reporting on results for P budgets from 71 farms in nine different temperate-zone countries; Nesme et al. (2012) covered 23 farms in the Dordogne region of France. But neither of these studies are on a scale that allows a comprehensive assessment of how P balances affect soil P levels. This highlights a need for further compilation and analysis of P balances from a range of organic farm types and environments/regions.

Factors influencing soil P status on organically managed fields and farms

The farm scale data was primarily from the Norwegian soil testing database (1163 values) which was likely dominated by livestock farming and non-arable systems typical of the region, ranging in size from 15 to 30 ha and including both pasture and arable land (Løes et al. 2015). The remainder of observations in the farm scale dataset were from the papers by Løes and Øgaard (1997, 2001), the Swiss farm survey data (Bosshard 1999) and one published Swedish study (Williams and Hedlund 2013), all representing primarily mixed farms. Several studies have reported slightly negative farm level P budgets on organic mixed farms. Goulding et al. (2000) calculated a nutrient budget for one mixed farm in England (upland farm with sheep and suckler beef) and reported a deficit of 0.2 kg P ha^{-1}. In a study in France Foissy et al. (2013) reported average P deficits of 4.6 kg P ha^{-1} for six mixed farms in the county of Lorrain where milk and cereals were the main exports. The study by Watson et al. (2002) summarized previously published farm scale nutrient budget information for six mixed farms in Germany, New Zealand and Norway, and reported an average P deficit of 2.4 kg P ha^{-1} $year^{-1}$. Since mixed farms are more likely to be self-sufficient in feed they are likely to import less P in feed, which may lead to a P deficit in the long term. Nevertheless, in all of these examples P deficits on mixed farms were not large, suggesting that with minimal imports of feed or fertilizer, P balances could be maintained.

Where the main product comes from livestock, farm scale exports of P will be relatively low. For example, the organic dairy farm at Newcastle University milks 108 cows and exports ~ 75,400 litres of milk per year which is equivalent to ~ 716 kg P (Watson et al. 2010). On this 130 ha farm the P exports amount to about 5.5 kg P ha^{-1} $year^{-1}$. This relatively small deficit may be partially offset through weathering of P minerals in soils which can release from 0.05 to 1 kg P ha^{-1} $year^{-1}$ (Newman 1995). Importing more concentrates, or increasing supplementation of P-containing mineral feeds, may also increase P excretion; this P may be more available to crops, since the very acidic environment in parts of the digestive tract of animals will mobilize most of the apatitic P compounds of mineral feed supplements (Shastak et al. 2012). For these reasons, P deficits on mixed organic farms may be minor and not reflected in soil test P values.

For a subset of dairy farms in Austria with data originating from the AGES (2010) study, a high proportion was in the low to very low range for soil test P. Likewise, the Swiss farm scale data indicated a problem with low or very low soil P levels (Fig. 3). There may be a link between the P status and the length of time these farms have been managed organically: some farms in the Swiss study had been under organic management for over 40 years, with one organically managed for 62 years. Although annual exports of P are expected to be small on these farms, imports of fertilizers to balance exports are minimal or non-existent and may lead to P deficiencies in the long term (Mäder, personal communication). However, correlation of the Swiss P-DL results with the numbers of years under organic management indicated only a weak negative relationship.

The field scale data indicated problems with low levels of available P in about 40% of arable and grassland fields (Fig. 1b), while horticultural land tended to have sufficient or high soil P availability. This reflects the results of Watson et al.'s (2002) study of organic farm nutrient budgets which reported a mean surplus of 38.9 kg P ha^{-1} $year^{-1}$ for horticultural operations, with most other systems running a P deficit. The surplus for the horticultural systems was attributed to the regular import of solid animal manures which are applied primarily as an N source, and can result in accumulation of P in soil (Cuijpers et al. 2008; Zikeli et al. 2017). Approaches to decrease excess levels of P imports on organic horticultural farms could include increasing the share of N inputs provided by biological N_2 fixation or replacement of P rich solid organic amendments with amendments with a wider N/P ratio (Zikeli et al. 2017).

The field scale data are overwhelmingly represented by German and Austrian fields, where animal and arable farming activities are segregated. This significantly affects overall nutrient flows and budgets. The low soil P levels in arable systems (Figs. 1b, 2) may be related to national interpretations of organic standards, since in both Germany and Austria national standards restrict the use of conventional animal manure limiting its use as a P source in these countries

(Schmidtke, personal communication). In Norway, where only EU regulations restrict the use of conventional manure in organic farming (Løes et al. 2017), the values are generally much higher (Fig. 3).

Organic farmers who do not import conventional manure may rely on legume leys in rotation to provide fertility to the crop. Legume leys can provide significant amounts of N to subsequent crops through biological N_2 fixation, which in the short term may result in maintenance of soil fertility and economic yields, however, supplementary P fertilizer still needs to be provided to replace P exports from the field. If this is not done, P deficiencies can develop which can limit other processes having a direct impact on yield, such as symbiotic N_2 fixation (Oberson et al. 2013) or the release of P from crop residues (Damon et al. 2014). Since the symptoms of N shortage are immediately visible, while the effects of P deficiencies are usually only evident over a longer time period, growers' attention is often focused on providing an adequate N supply to crops to the detriment of P supplies in the long term.

As an example of the impact of extensive use of legume leys in the crop rotation on farm level P balances, we have calculated P balances for typical arable rotations that may include 2–3 years of red clover or white clover ley followed by 3–4 years of arable cropping, using figures from Watson et al.'s (2010) Guide to Nutrient Budgeting on Organic Farms. If these systems involve no removal of the biomass during the legume phase i.e. mulching of the green manure, in addition to the import of compost and/or manure at least once during the rotation, then the net P balance should be positive. If the legume ley is harvested and removed from the field as silage to provide the farmer with some economic return from the land during the ley phase, and some poultry manure is provided at one stage of the rotation, then the net P balance is still slightly positive. However, if the ley is harvested and no fertilizers are added to replace exported P, then the system has a net P deficit of approximately 61 kg P ha^{-1} over 5 years or about 12 kg ha^{-1} $year^{-1}$. This figure corresponds with other surveys showing strong P deficits for stockless arable systems with low external inputs, with net farm P exports varying between 7 and 16 kg P ha^{-1} $year^{-1}$ and averaging approximately 11–12 kg P ha^{-1} $year^{-1}$ (Berry et al. 2003; Lindenthal 2000; Möller and Stinner 2010). This level of P export could result in declines in P-CAL of 1 mg kg^{-1} soil $year^{-1}$ (Römer 2009). Hence, arable farming practices including over-reliance on legume leys are resulting in negative P balances which are causing reductions in soil available P in the long term (Cornish 2009). Assessments for the entire organic sector in Germany including all types of production systems indicated that average P budgets range between − 16 kg and + 26 kg P ha^{-1} $year^{-1}$ (Kolbe 2015). The mean net farmgate P budget i.e. the need for additional external P inputs to replace exports, was approximately − 5 kg P ha^{-1} $year^{-1}$ across the entire organic sector (Kolbe 2015). Based on Römer's (2009) findings, this level of P export would result in an expected average decline in P-CAL of 0.5 mg kg^{-1} soil $year^{-1}$, providing an explanation for the low levels of extractable P reported for some organically managed fields in our study.

The challenges with maintaining an appropriate P balance on organic farms is partly related to the strong focus on the N cycle, combined with a lack of awareness about the potential long term impacts of imbalanced mineral nutrient supply, and further exacerbated by a scarcity of efficient off-farm P sources for the organic sector. The absolute prohibition on use of any P source derived from wastewater treatment systems, and limitations on other sources of recycled P, leads to a scarcity of efficient P fertilizers for use on organic farms in Europe (Løes et al. 2017), which may also be a partial explanation for the trend towards declining soil P discussed here.

Are conventional soil P extractants applicable in organic systems?

While we have reported trends towards low levels of soil extractable P on some organic farms in Europe, soil test results should always be interpreted with caution. There is a broad body of literature discussing the merits of current fertilizer recommendations based on estimates of nutrient availability using soil extractants, even for conventional farming (Steffens et al. 2010; Taube et al. 2015). All of the common P extractants provide only an indication of the size of the P pools currently or projected to become available during a typical growing season. These extractants work by dissolving precipitated forms of phosphorus as well as enhancing desorption of P from the surfaces of clay minerals or Fe and Al oxides, however, they do not always account for other pools and processes that may impact on soil P availability, particularly in organic systems (Steffens et al. 2010).

Organic farmers may be more dependent on P supplies from mineralization of organic P than conventional farmers. They frequently rely on manure and compost as P sources, which can build up pools of soil organic P, particularly that bound in the microbial biomass (Richardson and Simpson 2011), even though the P in manure and compost is largely bound in mineral P forms (Frossard et al. 2002). Studies using the long-term DOK (bio-dynamic, bio-organic, conventional) trial in Switzerland have shown that organically managed soils contain more microbial P (Oberson et al. 2010) which turns over faster than pools in conventional treatments (Oehl et al. 2001). In the same experiment, basal organic P mineralization was greater under bio-dynamic than conventional cropping with only mineral fertilizer inputs (Oehl et al. 2004). This evidence suggests that microbially mediated processes in P cycling and supply of available P to crops could be more important in soils under organic cropping than in conventionally managed soils.

Release of P from organic pools can also be enhanced by flush effects, i.e., the release of microbial P in response to sudden changes in living conditions, which may be more pronounced under organic cropping (Oberson et al. 1995). In addition, a diverse population of soil fauna and flora may contribute to P release, e.g. bacterial grazers like nematodes, may release P held in the bacterial biomass (Becquer et al. 2014). Finally, the action of beneficial soil organisms such as mycorrhizal fungi which facilitate uptake of P from less soluble pools in the soil may be more important in organic systems (Piotrowski and Rillig 2008). The magnitude of these processes is not assessed by conventional soil P extractants. As a result of this, it is reasonable to assume that conventional soil P extractants may be underestimating P supply in some organic farming systems. This is the perception of organic farmers in parts of Germany who assume that a soil test value of 21–44 mg P kg^{-1} using the P-CAL method is sufficient in organic systems (Kolbe 2015), although a value in this range is categorized as "low" within the current German system.

Do organically managed crops have higher P use efficiency?

It is possible that crops grown under organic conditions with lower levels of available P develop mechanisms to improve the efficiency of both soil P uptake and internal utilization. Foraging for P may be improved through enhanced lateral root and root hair growth, and increased proportions of root cortical aerenchyma cells (Richardson et al. 2011). Fast and early root proliferation (root vigour) has also been identified as important for P uptake, with variability among genotypes indicating the potential for selective breeding to enhance this trait (Wang et al. 2016), as well as enhanced associations with mycorrhizal fungi as discussed above. Internal P use efficiency may also be enhanced through varietal selection. Various studies have demonstrated variations in shoot mass of crops per unit of P uptake among genotypes, which indicates an ability to produce biomass with lower internal P concentrations (Hammond et al. 2009; Ozturk et al. 2005; Vesterager et al. 2006). These mechanisms may be interacting to improve phosphorus efficiency in any situation where soil extractable P is low, such as under organic management, allowing yields to be maintained at lower levels of soil P and with lower levels of inputs.

Further research is required to determine if the low soil P status detected in some systems in our study actually results in lower crop yields. Nevertheless, crops grown under low P conditions are much more susceptible to environmental stress, which is expected to increase due to climate stress in the future (van der Bom et al. 2017). The need to replace P deficits at the farm scale highlights the importance of studying the safety and efficiency of various societal waste streams that may be considered as alternative P fertilizers by the organic sector.

Conclusion

For the soil test results accessed in this study, a proportion of organic farms or fields had very low or low available P status. This was mainly the case for arable and grassland fields, and in some cases also for organically managed dairy and mixed farms. These levels may be associated with negative P farmgate budgets often observed in organically managed farms, indicating the need for a re-design of the overall farm fertility management in the sector. Our results highlight a genuine issue in the sector, with declining soil P status potentially leading to reduced farm productivity. Better access to relevant data, possibly by establishing open access databases compiling anonymised farm management data, would be useful to assess whether our assumptions are justified. There is also a need for more research to establish meaningful soil P test methods and class boundaries for soil testing in organic systems. This would improve the credibility of conventional soil test results in the organic sector so that they could be used for more proactive approaches to P management on farms.

In the long term, soil P needs to be replenished by recycling waste from urban areas back to farmers' fields. New waste treatment technologies are rapidly developing. Coupled with improvements in techniques to assess environmental and human health risks, the time is indeed ripe to consider whether the range of allowable P inputs in organic farming systems should be expanded to improve the productivity and sustainability of the sector.

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